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TRIP REPORT AND RECOMMENDATION

REGARDING

COFDM

submitted by the Task Force on COFDM

of the Transmission Expert Group

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TABLE OF CONTENTS

EXECUTIVE SUMMARY AND RECOMMENDATION

The authors of this report form a Task Force within the Transmission Group that has been charged with investigating COFDM (Coded Orthogonal Frequency Division Multiplexing) technology for application to North American terrestrial television broadcasting: This report summarizes the facts learned and the interpretations shared by this Task Force as a result of a trip during the week of November 28, 1993 to laboratories in Europe that are developing and advocating COFDM. We visited HD-DIVINE in Stockholm, Thomson LER in Rennes, and had a combined meeting in Rennes with staff of CCETT of France and NTL / ITC of the United Kingdom.

For digital ATV, COFDM is a potentially viable technology, subject to additional development beyond that shown in any laboratory today. Its claimed advantage over single-carrier techniques, such as QAM and VSB, is a higher degree of ruggedness against large, multiple, static ghosts. COFDM can tolerate many combinations of multiple 0 dB ghosts with time delay within a defined guard interval, although exceptions have been found to this phenomenon in the literature. Single-carrier systems with conventional equalizers can handle ghosts 3 dB below the desired signal, depending on the time delay of the ghost and the length of the equalizer hardware; handling long-delay large echoes increases the complexity of the equalizer hardware.

At present, there is no COFDM system at the data rates required for television broadcast that can handle rapidly time-varying multipath or mobile reception.

Practical consumer receiver circuits are not as developed in the COFDM projects as they are in the North American QAM and VSB proposals. A primary example of such a practical issue is tolerance of phase noise in consumer tuners and typical cable delivery systems. These and similar matters are not "simply" topics for receiver design, but rather they must be addressed at the overall system definition stage. The narrow bandwidth of the individual COFDM carriers requires fundamentally more advanced approaches to handling receiver technology and design problems. Not all of the COFDM hardware demonstrations had implemented carrier acquisition and data synchronization, nor had they used practical, low-cost oscillator technology.

The peak-to-average power of a COFDM signal is on the order of 10-13 dB, although this range is subject to measurement and verification. Values of 6-7 dB have been measured by ATTC for single-carrier systems.

TRIP REPORT AND RECOMMENDATION REGARDING COFDM

Introduction

The Transmission Expert Group is charged with making a recommendation for modulation format for the North American ATV system. As such, we are analyzing and testing the Quadrature Amplitude Modulation (QAM) and Vestigial Sideband (VSB) proposals in forms that contain improvements from the first round of ACATS testing. The Group is also charged with investigating the status of algorithm and hardware development of Orthogonal Frequency Division Multiplexing (OFDM) techniques.

Toward this end, a Task Force within the Expert Group[1] traveled to Europe during the week of November 28, 1993. We visited HD-DIVINE in Stockholm, Thomson LER in Rennes, and had a combined meeting in Rennes with staff of CCETT of France and NTL / ITC of the United Kingdom. We are particularly grateful to Percy Ekedahl Pettersson of HD-DIVINE[2] and Vincent Michon of CCETT[3] for informative and gracious meetings and for hosting our visits.

There is much cooperation and information exchange among the companies developing COFDM in Europe. Nevertheless, some differences in approach and in development status are evident. It seems to us that greater concentrated effort and more shared development exists among the French and English companies than at HD-DIVINE. There seemed to be more practical development and more willingness to discuss implementation problems realistically.

For the rest of this report, we will discuss OFDM with the addition of trellis coding; we will refer to that technique as COFDM. Without the coding, the performance of OFDM is unacceptable for terrestrial broadcast at ATV data rates.

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[1]The members of this Task Force are John Henderson (Chairman), Harvey Arnold, David Bryan, Lynn Claudy, Carl Eilers, Brian James, Louis Libin, Woo Paik, John Stewart, and Victor Tawil.

[2]When we visited HD-DIVINE, we also met with Staffan Bergsmark, Per Mellberg, Staffan Nystrom, Goran Roth, and Erik Stare, all of Teracom Svensk Rundradio. We also were entertained at dinner by Sven Olof Ekholm of Sveriges (Swedish) Television.

[3]Other staff members with whom we met at CCETT included P. Combelles, Bernard Le Floch, B. Marti, and J. Richard. We also met with Gregory Bensberg of ITC, Jeff Gledhill and Arthur Mason of NTL, and Jean Chatel, Jean Loisel, and Raoul Monnier of Thomson-CSF. We were entertained at dinner by D. Pommier of CCETT.

COFDM should neither be dismissed lightly nor embraced uncritically. COFDM offers a potentially viable modulation technique, subject to considerable additional development, for terrestrial television broadcasting. It can provide a high degree of ruggedness against large, multiple, static ghosts. COFDM appears to offer no advantages for cable, compared with single-carrier systems such as QAM or VSB.

Despite the strong multipath performance, significant design attributes for a practical consumer television COFDM system have not been developed. Moreover, there is no specific system ready for consideration and testing by the Advisory Committee at this time. It is the opinion of the Task Force that a candidate COFDM system could be developed and built within approximately 9-15 months, although we could learn of no such activity in Europe. If an effort is undertaken to create a COFDM system for North America, the approach must include a system design phase with flexible hardware and simulations to optimize COFDM parameters to a practical combination of ruggedness, data rate, and low-cost consumer receiver circuitry.

The rest of this report attempts to develop these points more fully and outlines the tasks and estimates the time to create a North American COFDM design, if that proves desirable.

Overview of Status of Algorithm & Hardware Development

A detailed summary of the individual systems we saw is presented in a later section of this report. In this section, we will present a more general overview of the state of COFDM technology world-wide. This section offers a composite of the capabilities of the several systems that we have seen and understood.

The claimed strength of COFDM is in its tolerance of high levels of multipath. An attribute of COFDM system design is a “guard interval” in the time domain; multipath whose delay times fall within the guard interval does not contribute to intersymbol interference. This guard interval provides multipath tolerance additional to the inherent tolerance of the narrow bandwidth (and hence long symbol time) COFDM modulation. We witnessed a demonstration of a partially implemented system in which it was shown that large echoes (one of 0 dB with respect to the main signal and one or more of the same or lesser amplitude) within the guard interval *may* add constructively to reduce the bit error rate. An often-repeated claim is that this phenomenon is universal for all cases of more than one echo and that this performance is unique to COFDM. COFDM advocates often describe a "worst case selective channel" consisting of a single 0 dB echo causing very deep notches in the frequency domain; the assertion is made that once the performance curve is established for the "worst case selective channel", additional echoes within the guard interval will always improve performance. However, this single echo worst case selective channel concept is not supported in the literature (see Appendix for further discussion). An example of a (much) worse channel is given in the standard reference test for digital communications by Proakis[4]. MIT researchers have also stated[5] that they have been unable to verify the concept of a worst-case selective channel by analysis. We believe that some combinations of echoes could make the channel worse and could conceivably overwhelm the trellis code.

The multipath performance of COFDM may offer a good match to the planned European broadcast environment of Single Frequency Networks. Such networks generate their own 0 dB "multipath," and the maximum time duration of the delayed signal is well-specified by the network topology. The required COFDM guard interval can then be determined precisely. This deployment of single-frequency networks may be an important difference between the European ATV distribution plan and that in North America. A separate issue is specification of the level and delay time of multipath that would represent a reasonable design goal for North American terrestrial broadcast.

Strong multipath creates spectrum shaping, including deep notches, in the frequency domain of the COFDM signal. This has two implications. The "notched out" carriers, and hence their information symbols, are tolerated only because of the addition of redundant information in the form of trellis coding. This redundant information reduces the payload data rate. In order to provide a payload rate suitable for HDTV video, more dense modulation constellations are used than those typical of the North American proposals (we saw COFDM systems with QAM constellations ranging from 16-states to 256-states). These more dense constellations impact negatively on the required signal-to-noise ratio.

The other requirement imposed by frequency notches and dense modulation constellations is gain and phase adjustment of each individual carrier. This requires that a complex multiplication be applied to each carrier. Because the COFDM symbol rate per carrier is so low, a single hardware multiplier can be time-shared. A training signal is required to determine the coefficients for this multiplication step. Its repetition rate determines the response time as well as the data capacity lost to this channel characterization function. The penalty is

[4] Digital Communications, Second Edition, John G. Proakis, McGraw-Hill, New York, 1989, pp. 572-574, especially, Figures 6.4.7-6.4.8c.

[5] At the MIT Workshop on High Data Rate Digital Broadcasting, October 26-27, 1992, at MIT.

not hardware complexity, but response time to dynamic multipath or to multipath in mobile reception. It is noteworthy that none of the systems we saw or discussed is designed for or intended to accommodate rapidly time-varying multipath conditions or mobile reception; the European target was reported to us to be fixed reception of HDTV and portable reception of standard TV. We should note also the distinction between the COFDM proposals for television broadcast and those for digital audio broadcast. The lower audio data rate permits very simple constellations (e.g., QPSK), which do not require the complex multiplication step and its associated training signal. These low rate systems will tolerate mobile reception and dynamic multipath, but they will not support ATV data rates.

All modern COFDM systems feature use of the Fast Fourier Transform (FFT) as a key hardware element. This permits mapping the data onto many carriers (as many as 5500 in some of the systems we discussed) in a hardware-efficient manner. It is sometimes claimed that the FFT offers receiver simplification compared with the equalizer employed in most single-carrier systems (e.g., the QAM and VSB systems proposed for North America). It is certainly true that multi-tap equalizers implemented in the simplest conceptual way are extremely hardware-intensive devices - probably the largest single aggregate of silicon in an HDTV receiver. However, equalizers can also be implemented using an FFT, somewhat mitigating the claimed simplifications of COFDM. In general, we do not believe that there are important differences in overall complexity of the digital portions of the circuitry between COFDM and the single-carrier systems we have been testing in North America; there may be some cost penalty in the analog RF portions of the tuners required for COFDM.

It seemed to us that less importance has been attached thus far to practical consumer receiver circuits in the European COFDM development projects than is attached to these practical issues in North American ATV. This is not a criticism of the work underway or the seriousness of the effort. It is instead a statement of the development schedule under which the European programs operate. They are looking toward system implementation in about the year 2000 and are properly emphasizing more fundamental design concepts at this early stage. However, the lack of consideration of some cost-sensitive elements of the complete receiver is a comment on the readiness of COFDM for the North American schedule. A primary example is tolerance of phase noise from consumer tuners or typical cable TV delivery systems. Tolerance of this impairment is worsened by use of multiple, narrow-band carriers, but COFDM systems are driven to multiple, narrow-band carriers in order simultaneously to provide a high data rate and a wide guard interval to tolerate multipath.

Not all the systems we saw implemented carrier acquisition and data synchronization, and yet these are fundamentally difficult and important system issues. Even in the demonstrations where the hardware was "complete" in this regard, it did not seem to us that frequency pull-in range and acquisition time had received much attention as yet; the hardware at this stage used laboratory-grade frequency synthesizers instead of practical receiver circuits. There was a variety of synchronization schemes among the different systems, which strengthened our opinion that development in this area is not yet mature.

The ratio of peak-to-average power has been an important issue for COFDM because of its impact on transmitter requirements and its impact on interference to co-channel NTSC. The worst-case ratio can be on the order of 27 dB (or even more, depending on the number of carriers in the COFDM system), but the probability of this value is vanishingly small (it depends on the modulation lining up the amplitudes and phases of all carriers exactly). We believe that a more realistic design ratio of peak-to-average power is on the order of 10-13 dB. These values, however, may be different when subjected to measurement and verification. Values of 6-7 dB have been measured at ATTC for single-carrier systems.

Although COFDM could work over cable, there is no discernible advantage to COFDM in a cable environment. It was suggested that terrestrial broadcast modulation could be COFDM and that cable modulation could be something else (e.g., Europe seems to be converging toward use of 64-QAM on cable). This was not stated by anyone with consumer equipment manufacturing responsibility (indeed, all our discussions were with professional equipment manufacturers or broadcasters); the practicality of such a design seems unlikely at first pass, although no formal study has been initiated.

European Activities Toward COFDM Development

The Approach to Digital Broadcasting R&D in Europe

For application to terrestrial broadcasting, all current European development projects incorporate COFDM technology as the transmission method of choice. However, the specific details of system implementations may differ between projects, such as selection of guard band interval, number of carriers, synchronization method and so forth.

All European organizations pursuing COFDM development are doing so both independently and jointly. The four organizations that met with the US. delegation (HD-DIVINE, CCETT, Thomson CSF and NTL) are each involved in separate research efforts incorporating COFDM. However, they are also linked in a coordinated process that is expected to ultimately produce convergence on a single preferred approach for application throughout Europe.

Operational Projects

A. EP-DVB

Following an initial decision in 1991, the European Project on Digital Video Broadcasting (EP-DVB) was formally established in September 1993 by a Memorandum of Understanding signed by some 100 participants. The target of EP-DVB is to create in Europe a framework for a harmonious and market driven development of digital television via cable, satellite and terrestrial broadcasting. The participants of the DVB Project are broadly based including national administrations, satellite and cable operators, private and public broadcasters, manufacturing industry and network providers.

The time scales developed for the EP-DVB project are as follows:

-- end of 1993 -- draft European standard for broadcasting via satellite and cable;

-- end of 1995 -- draft European standard for terrestrial broadcasting.

It was stated that both COFDM and single carrier 64-QAM are under consideration for the cable transmission standard in the EP-DVB activity, whereas only COFDM is being pursued for terrestrial broadcasting. This topic was not directly discussed by the European representatives meeting with the FCC Advisory Committee delegation.

Within the EP-DVB Technical Module (equivalent to a subcommittee), the operational projects of dTTb, HD-DIVINE and $^{H}DTV_{T}$ are being considered.

B. dTTb

dTTb (digital Terrestrial Television broadcasting) was begun as a CEC project in 1992 and is currently funded for 12 M ECUs(approx. $13.5 M) for 1994/95. The dTTb project is specifically focused on terrestrial broadcasting of digital video and includes 35 partner organizations. Both NTL and CCETT participate directly in dTTB. dTTb also has official liaison paths with both HD-DIVINE and $^{H}DTV_{T}$. The service goals of the dTTb project are fixed reception of HDTV and portable reception of SDTV using single frequency networks and dense/cellular networks. The current schedule is as follows:

March 1994 -- finalize specifications for initial demonstration unit
December 1994 -- Demonstrations of hardware
1995 - Field trials and public demonstrations
End of 1995 -- Final specifications and hardware configuration

C. CCETT

CCETT is a joint venture of France Telecom and TDF. Of the 385 staff members, 263 are research staff. CCETT operates at a budget level of 87.5 MF (approx. $15.6 M). CCETT's contribution to dTTb is embodied in the STERNE (Systeme de TElevision en Radiodiffusion NumeriqE) project. This is focused on channel coding and optimization of the COFDM transmission system. The CCETT prototype hardware was demonstrated at the Montreux International Television Symposium in June 1993 (using 448 carriers and 16 QAM modulation) and a second more advanced prototype was developed for the October 1993 ITU-RS meetings in Geneva (896 carriers, 64 QAM modulation). This hardware was shown to the FCC Advisory Committee delegation.

D. Thomson CSF

The Thomson project concerning COFDM technology is called DIAMOND. The Thomson laboratory facility in Rennes (Thomson LER) is specifically focused on digital modulation and coding aspects of imaging research and is also active in pursuing avenues for commercialization of advanced telecommunications products. They have developed a COFDM modem that can transmit a 34 Mbps TV signal (one HDTV signal or four SDTV signals) in one 8 MHz channel when working with a single polarization or two 34 Mbps signals using dual-polarized transmissions on the same channel. This unit was demonstrated to the FCC Advisory Committee delegation.

E. HD-DIVINE

HD-DIVINE (DIgital VIdeo Narrowband Emission) is a separate company formed through a collaboration of the following Nordic organizations: Teracom, Swedish Telecom, Sveriges Television, Telecom Denmark and Telecom Finland

The goal of HD-DIVINE is to develop a digital TV/HDTV system which can be introduced in Europe before the year 2000. In the January 1991-July 1992 time period, HD-DIVINE focused on proving the feasibility of their concept, culminating in demonstration of an initial prototype in June '92 at IBC. In the period from August 1992 to March 1993, efforts were focused on finalizing the OFDM modem, official formation of the DIVINE company, and developing the version 1.0 system. From April '93 until 1996, efforts will be aimed toward a September 1995 demonstration of the version 2.0 system at IFA in Berlin, and submitting an ETSI proposal for a standard. The version 2.0 modem will include more powerful capabilities and flexibility for parameter adjustment through a pc interface.

In January 1994, experimental transmissions in Sweden for cable will be initiated and an early version of the 2.0 system will be shown at IBC in Amsterdam in September 1994. Final specification for the version 2.0 will be determined by December '94.

F. NTL

The SPECTRE (Special Purpose Extra Channels for Terrestrial Radiocommunication Enhancements) project was started by the Independent Broadcast Authority (IBA) in 1988. In 1990, the IBA engineering and transmitter operation responsibilities were transferred to a privatized organization, National Transcommunications Limited (NTL). The regulatory activities of IBA for television were transferred to the Independent Television Commission (ITC). The SPECTRE project is being performed by NTL under contract to ITC. SPECTRE research has concentrated on field tests of uncoded OFDM transmissions at field test sites in the U.K. and development of optimized channel coding based on the propagation conditions encountered in the field. The NTL hardware is flexible and can support different configurations of COFDM parameters through software adjustments.

G. $^{H}DTV_{T}$

$^{H}DTV_{T}$ (Hierarchical Digital TV Transmission) is a German project which is focusing on hierarchical source coding methods as well as satellite transmission methods. The project includes about ten partners under the chairmanship of the Heinrich-Herz Institute (HHI). The Advisory Committee delegation did not coordinate with representatives from the $^{H}DTV_{T}$ project.

Summary of the Systems & Explanation of Differences

Table 1 summarizes the parameters of the various OFDM systems, both existing and proposed, that we discussed. The wide range is evident and is a "feature" of OFDM.

HD-DIVINE

HD-DIVINE Version 1.0 Modem for 8 MHz Channels

Like many European organizations, HD-DIVINE based its version 1.0 OFDM modem parameters on those used for Digital Audio Broadcasting (DAB). Thus, for example, they used 448 active carriers. The modulation per carrier was upgraded from QPSK (used for DAB) to 16 QAM. They were then able to increase the useful bit rate to more than 25 Mb/s. A distinguishing feature of the 1.0 modem is its very short guard time, HD-DIVINE reported that their investigations showed that most echoes of significant power fell within the 2 us they allocated to the guard interval. This assumed only "natural" echoes (not caused by SFN) and use of directional antennas. In subsequent documents they suggested that a 32 us guard interval should be used in an SFN environment. During the visit they likewise stated that the 2 us guard interval "should be longer". FEC was RS only, technically part of the video codec.

HD-DIVINE Version 2.0 Modem for 8 MHz Channels

Recognizing that the guard time and FEC provided in version 1.0 were probably not sufficient, HD-DIVINE has begun to establish the parameter set for version 2.0. Examination of Table 1 shows that their goal for Version 2.0 is near total flexibility. They will be able to have up to 13,000 active carriers, allowing very long guard times if required. The modulation per carrier can be varied from QPSK to 256 QAM as required to deal with "bad" areas of the band. The total bandwidth will be flexible and can be adapted for 6 MHz channels. Most of the other significant parameters including data rate, number of carriers and width and placement of any spectral cutouts will also be variable. Nonetheless they mentioned that trellis coded 64 QAM per carrier "may be the most interesting" modulation.

HD-DIVINE Strawman for 6 MHz Channels

The second-to-last column in Table 1 lists a very tentative set of parameters that might apply to the US. and other 6 MHz countries. Note that the guard time proposed is now 32 us. Also notable is the extremely large number (5500) of active carriers. This choice allows them to use the relatively long guard interval and still maintain the requested approximate 19 Mb/s net bit rate. However, such a large number of carriers would be cause for concern, particularly in regard to phase noise and bit precision requirements, which are discussed in later sections.

Thomson CSF LER

Again they based their initial design on the DAB parameters but quickly upgraded to 64 QAM per carrier, which by the time of our visit had been upgraded to trellis-coded 256 QAM. Because they require that I and Q are separately trellis coded, 3 uncoded bits/symbol each for I and Q become 4 trellis coded bits/symbol each for I and Q. Hence trellis-coded 256 QAM. Of course the C/N threshold for this modem is rather high (22 dB ?), but the goal of LER has so far been a very high data rate (34 Mb/s). Their modem shows interesting equalization and synchronization features not found in other designs. They use a fairly high overhead(1/15 of all symbols) for equalization, which should lead to more robust operation than some designs in the face of rapidly time-varying multipath conditions. On the other hand they use two fixed carriers for synchronization, which may not be as robust as other designs (see synchronization, below). For example it might be a problem in a channel with deep notches at the fixed carrier positions. LER is also notable for a near-doubling of the data rate when they use dual polarization. However they did state that this would require two antennas.

CCETT

CCETT Lab Prototype

CCETT is notable as the "father" of DAB and perhaps has the greatest depth of theoretical knowledge regarding OFDM. Thus although they no doubt based their high speed modem work on the previous work done on DAB, their current Lab Prototype design shows considerable variation from the original parameters. For example they already use about twice as many carriers as the other existing prototypes. They established a long guard interval (32 us) perhaps anticipating SFN's. But they acknowledged that recent studies on SFN now indicate that guard intervals of 100 us or more might be needed. They are very active in coding and their current prototype features trellis-coded 64-QAM. They are also very active in developing turbo codes, which promise even better performance than trellis coding. In addition to patenting the use of time/frequency interleaving with OFDM, they have also made many innovations in the areas of equalization and synchronization, some of which will be discussed in more detail below. They were able to demonstrate, with partially implemented equipment, multipath resistance for 0 dB echoes within the guard interval, which is quite impressive. However it must be mentioned that their synchronization schemes have not been realized in the prototype itself. Thus the prototype is not suitable for actual on-air testing, as the carrier is hardwired from transmitter to receiver.

CCETT Strawman for 6 MHz Channels

The CCETT Strawman is perhaps best compared to the DIVINE Strawman, as all of the other designs are oriented towards 8 MHz channels. To meet our request of nearly 19 Mb/s data rate, CCETT has opted for increasing the number of carriers to 1386 (data bearing). They have maintained the 32 us guard time of their 8 MHz prototype. Still they may come up a bit short on data rate as they end up with a gross data rate of 19.096 Mb/s which has to include overhead for the outer (RS ?) code. This is why DIVINE chose to go for 5500 carriers. Nonetheless the CCETT design perhaps comes closest to being realistic for 6 MHz channels, as the net data rate would probably be only slightly lower than the Grand Alliance systems and the phase noise problem would be much less severe than for the DIVINE strawman. We should note the longer frame time in the CCETT strawman versus their prototype, which might make equalization and synchronization somewhat less robust.

NTL

NTL did not really describe or propose a parameter set during our visit, but some of the parameters of their prototype can be found in their publications. These are listed in Table 1. The NTL parameter set is again based on original DAB and in fact includes QPSK modulation as in DAB. Apparently they have concentrated more on how to implement digital standard definition television and thus have looked at QPSK, 8PSK and 16 QAM per carrier. Their focus has been more on transmission testing (discussed below) than on a parameter set for HDTV. They don't appear to claim any FEC other than RS.

Explanation of the Differences

The differences in parameter choices illustrated in Table 1 can best be explained by the differing assumptions about system requirements made by the various organizations, as well as the level of effort expended by each (both in terms of time and manpower). This was not discussed in any detail on our visit but some observations can be made.

HD-DIVINE has oriented themselves toward HDTV from the start and thus always pursued high data rate. They believe that broadcasting to fixed receivers makes sense and that directional antennas will be used. This explains their initial choice of a short guard time. LER has pursued extremely high data rates, through the largest noted constellation and use of dual polarization. It seems that they initially wanted to be able to carry 34 Mb/s (perhaps x 2) which is a standard TELCO rate in Europe. CCETT is more varied but is very much interested in the SFN concept and thus has put a lot of effort into robust equalization schemes, including relatively long guard intervals. NTL seems to have focused on minimum practically achievable data rates that allow re-use of taboo channels, even if not sufficient for HDTV. However, these various organizations are now converging to a certain extent in that many of them have been participating in and may be involved with prototyping for the Europe-wide dTTb project. Thus we can expect considerable convergence on a common parameter set for Europe within the next couple of years.

Acquisition and Synchronization

HD-DIVINE Synchronization Scheme

In version 1.0, a basic OFDM symbol consists of a multiplex of 448 modulated carriers. An OFDM frame is built up by 509 such symbols preceded by 3 sync symbols. The contents and usage of the sync symbols are:

- Empty symbol (null), used for initial frame alignment and positioning of FFT window.
- Fixed sine wave, used for automatic frequency control of the demodulator.
- Chirp signal for channel estimation, equalization and sample clock recovery.

So carrier recovery uses a fixed sine wave (i.e. carrier burst). This corresponds to one time gated sync symbol per frame. They use the chirp signal for fine symbol timing recovery. This is correlated with a stored pattern in the time domain. Processing of the chirp uses time averaging (leak).

There is a fixed oscillator at the front end of the demodulator. A TMS signal processor is used for carrier tracking. Digital correction is done after the A/D in baseband. The carrier acquisition range is +/-10-20 kHz.

In version 2.0, the hardware will be able to use up to 3 symbols for sync; it will also be able to use fewer.

Thomson CSF LER Synchronization Scheme

For synchronization 2 unmodulated carriers are dedicated to clock and LO recovery. The phase evolution of these carriers is monitored. This processing leads to control signals that are sent to DDS chips.

Symbol tracking uses the phase discontinuity between symbols (0.8 us out of 8.8 us guard time). They look at the signal state in, e.g., the latter part of the symbol and compare it to the expected periodic extension in the guard interval. If they are off they will see a discontinuity between these two points.

The carrier frequency acquisition range is now 12 kHz. They stated that this could be improved. The two unmodulated carriers are situated roughly 1/4 and 3/4 of the distance across the band.

There is a more detailed discussion on the carrier synchronization scheme in the literature[6].

CCETT Synchronization Scheme

In the current implementation, the frame consists of 150 symbols, 3 of them being used for synchronization (2 % overhead).

Time synchronization is ensured by the use of 2 symbols. The first symbol is a null symbol, during which the transmitted signal is zero. The receiver detects the envelope of the signal and positions a time window on the useful part of the second time synchronization symbol. This null symbol provides a coarse time sync (positioning of the FFT window). An analog detector is used which is not good enough for the desired resolution of 1 us. A fly-wheel is associated with this detector for the case of noisy channels.

The second time sync symbol comprises unmodulated (fixed amplitude and phase) carriers. This symbol is a chirp signal (sine sweep). All carriers are used. This symbol is used in the receiver to extract the impulse response of the channel by correlation. The autocorrelation is done by FFT --> IFFT. The output of the autocorrelation process is the impulse response of the channel. This is used for fine time sync, as the correlation peak is the inverse of the

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6 See, for example, "Digital Television Broadcasting with High Spectral Efficiency", by Monnier, Rault, and de Couasnon.

signal bandwidth (1/7 MHz = 143 ns). This allows very accurate positioning of the FFT. This process takes place before carrier acquisition.

Frequency sync can also use the second time sync symbol. This process consists of correlating adjacent groups of carriers is the frequency domain and analyzing the leakage due to a frequency shift of the LO of the receiver.

Another type of symbol can also be used for this purpose. This was the third symbol in the first implementation (for DAB). This consists of a discrete comb of carriers (1/16). The FFT is taken and they look at the aliasing. This can be used to find the offset between the receiver`s tuner and the transmitter. The frequency offset can be greater than the carrier spacing; it can be +/- 7 carriers. In this case the reference carriers discussed immediately below will do for fine frequency/phase tracking. There is a conflict within the handouts and presentation notes as to whether this symbol is used in the current implementation.

Channel estimation (see Figure 1 from CCETT handout), uses reference symbols multiplexed in time. But only every Nth carrier within the reference symbols is used for channel estimation; the others carry useful data. These reference symbols are also used for fine AFC and to help combat phase noise. The distance between the reference symbols is related to the amount of phase noise and the variability of the channel. A little more detail on this use of these reference symbols is provided in the literature[7].

A block diagram of the coherent demodulation process is shown in Figure 2 (from the handout).

NTL Synchronization Scheme

The NTL modem has data-derived reference carriers that track phase noise for demodulation. These carriers are averaged using a simple recursive filter, according to: new ref. = alpha x data derived estimate + (1-alpha) x previous ref.

The main sync functions are symbol timing recovery (FFT start time), system clock recovery, and AFC. The first two may be the same function. Sync can be based on special symbols OR data directed.

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[7] "Trellis Coded Orthogonal Frequency Division Multiplexing for Digital Video Transmission", by Helard and Le Floch, Globecom '91, pp. 23.5.1-23.5.7.

There was no block diagram or information presented to us, although a paper on the NTL synch scheme exists[8].

Special Technical Issues

Peak-to-Average Power

The ratio of peak-to-average power of the COFDM is higher than QAM or VSB. The theoretical value of the difference depends on the number of carriers in COFDM and is determined by the following equation:

$$\Delta \text{ (in dB)} = \log_{10} N$$

where N is the number of carriers. For example, the increase in the ratio of peak-to-average power for a 500 carrier COFDM is theoretically 27 dB as compared to a single carrier QAM.

The limiting case where N becomes infinity can be modeled as bandlimited Gaussian noise since "Law of Large Numbers" dictates that the amplitude statistics will become Gaussian when the number of independent carriers is very large. Although the ratio of the peak-to-average power of Gaussian noise is theoretically infinite, the statistical distribution above 4 to 5 times the variance becomes negligible. Hence, the ratio of peak-to-average power of COFDM is, in reality, 12-14 dB. Furthermore, the ratio can be reduced further by employing a limiter followed by a bandpass filter, but because of the high power handling requirement there may be some leftover adjacent channel splatter. Therefore, the realistic design ratio of peak-to-average power is on the order of 10-13 dB, pending measurement and verification.

Phase Noise, Carrier Recovery

In any up and down conversion process a spurious phase-noise and frequency modulation process, including power supply hum and mechanical vibration are to be expected. At the transmitter up-converter, the use of an oven for the crystal oscillator operating of a fixed frequency together with a synthesizer or cascade of frequency multipliers can be effective in achieving a satisfactory phase-noise and frequency modulation specification with costs

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8 "The Transmission of Digital Television in the UHF Band Using Orthogonal Frequency Division Multiplexing", by Gledhill, Anikhindi, and Avon, IEE Conf. Pub. #340. This may be obsolete, based on what was presented.

affordable for transmitting equipment (cable modulator costs are more of a concern).

At the receiver, the down conversion oscillator(s) must be tunable over many frequencies. Electronic tuning using varactors is universal which means that a low-"Q" tank circuit is the result, making susceptibility to phase-noise a universal problem. The varactor is fed with a voltage which is a combination of an approximate selected channel frequency voltage (typically within 50 kHz to 100 KHz of the required frequency) and a voltage which is derived from an automatic frequency/phase detector to tune-in the local down-conversion oscillator to the correct frequency and phase for synchronous detection of the I and Q digital signals. The sensitivity to phase noise in numerical terms has only been reported by one of the OFDM proponents.

HD-DIVINE did not provide phase noise information but plan to study the problem. In their demonstration, only one channel could be tuned (with a crystal oscillator), and thus was not representative of a practical system.

At Thomson CSF the statement was made that phase noise must be contained within the carrier spacing. No analysis was offered. They have 2 carriers symmetrically placed with respect to the center of the channel for the dual purpose of clock recovery and local oscillator locking.

At CCETT the statement was made that phase noise greater than the carrier spacing cannot be tracked. In their demonstration they did not have up and down conversion but used the same carrier, hard wired between modulator and demodulator. They were aware of the problem and understood that the situation worsens with an increasing number of carriers (as might be required for a 6 MHz system). They recited their experience with NTL tests using PAL synthesized tuners with OFDM/4PSK as being just possible. It should be noted that the constellation distance for 32QAM is about ten times closer than 4PSK which re-emphasizes the phase noise problem. NTL proposed the solution of widening the synthesizer bandwidth in UHF tuners (wider than 4 kHz). They showed a plot which indicated a phase noise requirement of -55 dBc/Hz at 500 Hz offset, as opposed to -35 dBc/Hz for the unmodified PAL tuner. This just enabled them to operate with a 512 carrier 16QAM-OFDM system. They agreed that the phase noise requirement would be more severe for a COFDM system that would suit U. S. requirements, as such a system would probably require 64 QAM per carrier and might require 2048 carriers or more. A possible solution mentioned for such a system was the use of reference carriers (pilots) which track phase noise for demodulation instead of (or in addition to) data derived reference carriers. Many of these modifications require more lock-up time.

Synchronization, Acquisition

Various techniques have been employed to achieve bit timing, frame synchronization and acquisition. HD-DIVINE used 3 symbols (empty, sine wave, and chirp) per frame of 512 symbols (32 μsec). Thomson-LER used one special symbol per 15 symbols plus 2 unmodulated carriers. Both of these techniques suffer slow acquisition and tracking, too much overhead, or potential problem with loss of unmodulated carriers in certain multipath conditions. The slow tracking will reduce tolerance to phase noise.

CCETT developed the most sophisticated approach by sending special symbols in time-frequency interleaved manner. This will potentially provide fast acquisition and tracking with low overhead and without danger of losing special carriers in any multipath conditions. However, this approach has not been implemented or demonstrated as yet.

Receiver Cost, Complexity, Precision, Speed

An accurate assessment of the cost and complexity of a consumer grade COFDM receiver is difficult to estimate. One reason is lack of experience in building a consumer grade COFDM system. The prototype systems demonstrated were primarily intended to show the feasibility of a digital broadcast system and also to test the performance of COFDM in the field. The prototype systems were not intended to show the feasibility of a consumer grade COFDM receiver. Because of the original intention of the prototype systems, several key areas such as frequency acquisition, phase noise performance, and acquisition time have not been investigated thoroughly. This lack of information in key areas which impact the cost of the receiver do not allow for an accurate cost estimate.

The following paragraphs provide a comparison between a COFDM system and the current single carrier systems. For comparison purposes, the COFDM system is broken down into 5 sections. These are Tuner, Synchronization, A/D, Demodulation/Equalization, and Error Correction decoding.

The tuner for a COFDM system is similar to a tuner for a single carrier system except for the required phase noise performance. Currently, the demonstrated COFDM carrier recovery circuitry will only allow phase noise tracking within the bandwidth of a single COFDM carrier. This will require a tuner with excellent phase noise characteristics. Currently, consumer grade tuners with the required phase noise performance do not exist. Without further study, the cost and complexity of a COFDM tuner is not known but will be greater than for a single carrier system.

There were various algorithms used for time and frequency synchronization of the prototype COFDM systems. As mentioned above, several areas including frequency acquisition range and acquisition time have not been thoroughly investigated and may lead to more complex acquisition methods to obtain performance acceptable by a consumer. The complexity of all the current methods seemed to be about the same as those used for single carrier systems.

Due to the large dynamic range of the COFDM signals, the receiver A/D needs several more bits of resolution than is needed for the current single carrier systems. The demonstrated COFDM systems used A/Ds which ranged from 10 to 12 bits. These systems used between 512 and 896 carriers. If more carriers are used for a US compatible system the resolution of the A/D may need to be increased. The sampling rate for COFDM is roughly the same as for a single carrier system.

The major functional difference between a COFDM system and a single carrier system is the method of demodulation and equalization. In a single carrier system, both the demodulation and equalization are done in the time domain. In a COFDM system, the demodulation and equalization are done in the frequency domain. Demodulation in the time domain for a single carrier system is relatively easy, but equalization in the time domain typically requires 2N complex multiplies per input symbol with QAM and N/2 with VSB for an N tap equalizer. For a COFDM system, the demodulation process is the more difficult operation and is equivalent to an FFT over an N symbol interval. This requires log2(N) multiplies per symbol where N is the number of carriers used. For the systems demonstrated, N ranged from 512 to 896. The equalization for a COFDM system is relatively easy and requires only a single complex multiplier. The FFT ICs used in the COFDM prototypes had at least 16 bit resolution resulting in multipliers which are larger than those needed for a single carrier system. If it is assumed that the multipliers in the FFT are twice as large as those used in single carrier systems, then the overall complexity of the demodulation/equalization for a COFDM system with 512 carriers is roughly equivalent to a single carrier system with a 20 tap complex equalizer.

Finally, the error correction decoding complexity should be roughly the same between single carrier systems and a COFDM system. Both systems use convolutional and Reed-Solomon encoding for error protection.

The following table summarized the complexity/cost of a COFDM system as compared to a single carrier system. Overall, the complexity/cost of a COFDM system will be somewhat greater than a single carrier system.

Function	Relative Complexity/Cost compared to single carrier system
Tuner	Possibly much greater
Synchronization	Same
A/D	Greater
Demodulation/ Equalization	Slightly lower
Error correction decoding	Same

Summary of systems and explanation of differences

The following is a summary of the COFDM systems demonstrated

HD-DIVINE

512 carrier of which 64 can be removed for interference reasons
Plessey FFT IC is used in the receiver (16 bits)
16 QAM is the modulation type used
Current A/D precision is 12 bits
Each set of 512 carriers (referred to as a symbol) is 62.5 micro seconds long
A set of 512 symbols make up a 32 ms frame
Three framing symbols are used and include an empty symbol, sine symbol, and chirp symbol
Only Reed-Solomon error correction is used
No time or frequency interleaving is used

Thomson-LER system

512 carriers
16 bit Honeywell FFT IC
64 QAM with Trellis coding for 256 QAM constellation (I and Q separately coded)
10 bit A/D converter
8.8 micro second guard interval
Acquisition range +/- 12 kHz
Measured Peak to Average ratio 13 dB
Use two dedicated carriers for freq acquisition/phase tracking
Training symbol sent every 15 symbols
BER of 1E-7 at SNR of 23 dB

There were several differences in the Thomson-LER system and the HD-DIVINE system. First, the LER system did not use an empty symbol for time synchronization.

Instead, they used the phase discontinuity between the symbols for timing. This method may be more susceptible to echoes. The LER system also had trellis coding and used a 256 QAM transmitted constellation.

CCETT system

896 carriers
TRW FFT ICs
16 QAM trellis coded for 64 QAM (I and Q separately coded)
32 micro second guard interval
Frame consists of 150 symbols which is 24 ms
Dedicated Null, Chirp, and freq reference symbols
Equalization tones are distributed in both time and frequency
Currently, reference tones are sent every 4 carriers and every 4 symbols for overhead of 1/16
No carrier recovery was implemented at the time of the demonstration.

The CCETT system used more carriers than either of the other two systems demonstrated. This allowed a larger guard interval and therefore longer echo immunity.

Cable Issues

Cable television systems can take advantage of a transmission system capable of transmitting two ATV services in a single 6 MHz bandwidth. At this time the European advocates of COFDM have not considered the need for a high data rate on cable. Higher order modulation (256 QAM) with Trellis coding has been demonstrated for single channel terrestrial transmission. It is possible that the necessary data rate could be obtained with a reduced trellis code, increased number of carriers, reduction in the guard interval, etc., but this has not been investigated.

Phase noise and residual FM become a bigger problem on cable television systems due to the number of frequency conversions. The systems demonstrated used either highly stable oscillators or direct connection of transmitter to receiver. There appears to have been little investigation to date of the impact of and solution to the potential phase noise and residual FM problems.

The ATV signals carried on cable systems may be on non-standard channel assignments. The receiver must be capable of recognizing that the received signal is not on the standard frequency and then tuning to the required frequency. The systems demonstrated use "known" frequencies from quality synthesizers. The ability to identify and tune non-standard frequencies has not been demonstrated. This ability must be developed before COFDM is viable on cable systems.

Signals received at the subscriber's set are subject to changes in frequency response due to the tuning of TV sets located on the same drop and intermittent signal loss due to loose or poor connections. The ability of the COFDM systems to re-equalize, maintain lock or quickly recover the carrier and re-synchronize has not been demonstrated.

The European COFDM development has been aimed at terrestrial applications and not cable applications so little emphasis has been placed on the special requirements for cable implementation. The specific needs of the cable environment must be investigated before it can be determined if COFDM offers significant advantages in the cable environment.

Transmitter and Transmission Issues

The most compelling consideration for implementing COFDM is the claimed ability of the system to operate satisfactorily under severe ghosting conditions. This factor may increase the allowable level of transmission system mismatch (echo's and ghosting) in the transmission system. The selection of any transmission system which is more tolerant of transmission impairments will improve the transition to the new ATV service. Nevertheless, good practice would employ transmitter plant pre-equalization for both COFDM and single-carrier systems in order to remove additional burden on the receiver's equalizer. During previous demonstrations of earlier versions of 16-QAM COFDM equipment, those COFDM systems were shown to allow great latitude in receiver antenna selection, placement, and orientation. There are strong indications to believe that in many cases COFDM receivers could deliver satisfactory performance (in locations receiving high signal levels), without requiring the use of high-gain directional receive antenna systems. (Multipath performance is also discussed in several other sections of this report.)

COFDM (as well as single-carrier systems) may be suitable for portable reception with monopole antennas, providing there is an adequate received carrier-to-noise ratio.

The antenna systems design criteria used for transmission of COFDM should not be significantly more stringent than present day NTSC. Whether COFDM offers any advantage over single-carrier systems needs further investigation.

Transmission system requirements (linearity, noise and out-of-band emissions) for high power transmission of COFDM appear to be similar to that of single carrier ATV systems now being developed by the Grand Alliance.

Both low and high level envelope shaping may be required for single carrier and COFDM systems to insure sufficiently low out-of-band emission in the 7 MHz channel. Peak-to-average ratios appear to be 5-6 dB higher (subject to additional study) in COFDM systems. Unfortunately, none of the proponents employs the same methodology in evaluating peak/average ratios. It is not possible for us to critically compare the merits of single carrier systems to COFDM without having this measured data. The additional cost and complexity of transmission systems that must support transmission of modulation schemes employing high peak-to-average ratios can not be taken lightly. It is important to have a thorough understanding of this parameter since it directly affects the transmission system cost and spectrum planning considerations. (The issue of peak-to-average power ratio is also discussed in other sections of this report.)

COFDM proponents reported that some degree of carrier limiting (1-3 dB) could be used to reduce the higher peak-to-average ratios, but were unable to supply actual measured data relating to the trade-off between the degree of clipping and subsequent effects on usable system C/N ratios and data throughput. Additional transmitter power back-off may be required for COFDM systems for optimum performance. Again, additional assessment is needed.

Multipath

The major claimed strength of COFDM is its capability to handle high levels of multipath. CCETT demonstrated, with a partially implemented system lacking up and down conversion, that COFDM can handle multiple 0 dB echoes within the 20 μsec guard interval. In the demonstration, the error rate performance improved when more than three 0 dB echoes were present as compared to no echoes. The required C/N increased for the somewhat improved error rate. The required increased C/N at a given error rate was partially supplied by the added echoes. (See the Appendix of this report for further discussion of this point.) This capability is to be compared with the capability of single carrier QAM or VSB systems where ghosts of 3 dB below the desired signal are claimed to be tolerable depending on the location and number of the ghosts. Similarly, the single-carrier QAM and VSB systems have an increased C/N requirement supplied in part by the added echoes in increasing the carrier power and, depending on the ghost pattern, mat experience an improved error rate with added echoes.